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Tension and compression testing of fibre reinforced polymer (FRP) bars

Qasim S. Khan
University of Wollongong, qsk991@uowmail.edu.au

M Neaz Sheikh
University of Wollongong, msheikh@uow.edu.au

Muhammad N. S Hadi
University of Wollongong, mhadi@uow.edu.au

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Abstract

Corrosion of reinforcement in steel Reinforced Concrete (RC) columns significantly decreases both the strength and ductility of RC columns. Fibre Reinforced Polymer (FRP) bars have emerged as an attractive alternative to the traditional steel bars because of higher ultimate tensile strength to weight ratio and higher corrosion resistance of the FRP bars. However, Standard test methods for different types of FRP bars both in tension and compression have not been fully developed. This study presents the results of tension and compression tests of circular pultruded Glass FRP (GFRP) bars and Carbon FRP (CFRP) bars of 15 mm and 15.9 mm diameter, respectively. The tensile and the compressive properties of these bars were determined according to ASTM D7205/M7205-06 (tension test) and ASTM D695-10 (compression test) with some modifications. For tensile properties, three 1555 mm long GFRP bars and three 1555 mm long CFRP bars were tested in tension. For compressive properties, five 80 mm long GFRP and five 60 mm long CFRP bars were tested in compression. In tension, the tested FRP bars failed due to rupture of fibres whereas in compression the tested FRP bars failed due to separation of longitudinal fibres. The experimental results showed that the ultimate strength and modulus of elasticity of FRP bars in tension are 1.67 and 1.59 times greater than in compression respectively.

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TENSION AND COMPRESSION TESTING OF FIBRE REINFORCED POLYMER (FRP) BARS

Qasim S. Khan[1], M. Neaz Sheikh[2], Muhammad N.S. Hadi[3]

[1] Ph.D. Candidate, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia
Email: qsk991@uowmail.edu.au

[2] Senior Lecturer, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia
Email: msheikh@uow.edu.au

[3] Associate Professor, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia
Email: mhadi@uow.edu.au

Keywords: GFRP bars, CFRP bars, Tension test, Compression test

ABSTRACT

Corrosion of reinforcement in steel Reinforced Concrete (RC) columns significantly decreases both the strength and ductility of RC columns. Fibre Reinforced Polymer (FRP) bars have emerged as an attractive alternative to the traditional steel bars because of higher ultimate tensile strength to weight ratio and higher corrosion resistance of the FRP bars. However, Standard test methods for different types of FRP bars both in tension and compression have not been fully developed. This study presents the results of tension and compression tests of circular pultruded Glass FRP (GFRP) bars and Carbon FRP (CFRP) bars of 15 mm and 15.9 mm diameter, respectively. The tensile and the compressive properties of these bars were determined according to ASTM D7205/M7205-06 (tension test) and ASTM D695-10 (compression test) with some modifications. For tensile properties, three 1555 mm long GFRP bars and three 1555 mm long CFRP bars were tested in tension. For compressive properties, five 80 mm long GFRP and five 60 mm long CFRP bars were tested in compression. In tension, the tested FRP bars failed due to rupture of fibres whereas in compression the tested FRP bars failed due to separation of longitudinal fibres. The experimental results showed that the ultimate strength and modulus of elasticity of FRP bars in tension are 1.67 and 1.59 times greater than in compression respectively.

1 INTRODUCTION

Fibre Reinforced Polymer (FRP) bars have emerged as an attractive alternative of steel bars due to higher ultimate tensile strength to weight ratio, resistance to corrosion and chemical attack, electromagnetic neutrality, and long term strength and durability of FRP bars in harsh and corrosive environments [1, 2]. The widespread use of FRP bars in Reinforced Concrete (RC) members has yet been limited due to anisotropic and non-homogeneous material behaviour of FRP. Standard methods to test different types and diameters of FRP bars in tension and compression have not been fully developed. ASTM D7205M/7205-06 [3] only covers tensile testing of 6.4 to 32 mm diameter Glass FRP (GFRP) bars and 9.5 mm diameter Carbon FRP (CFRP) bars. A standard test method of compression testing of FRP bars has not yet been introduced [4]. The tensile testing of FRP bars is complicated due to significantly smaller shear strength of FRP bars than their tensile strength. Benmokrane et al. [2] successfully tested 7.5, 8.0 and 10.0 mm diameter AFRP bars and 7.9 and 8.0 mm diameter CFRP bars, whereas Kocaoz [5] tested 12.5 mm diameter GFRP bars in tension using expansive cement grouted steel tube anchors. Carvelli et al. [6] introduced a test arrangement consisted of conical resin heads which fits into the conical hole in the anchor for tensile testing of large diameter GFRP bars. Castro [7] reviewed different anchors used for tensile testing of FRP bars and recommended a testing arrangement consisting of FRP bar embedded in steel tubes filled with high strength gypsum cement mortar.

Fujisaki and Kobayashi [8] tested FRP bars embedded in concrete prisms at both ends with 5 mm clear length in compression and reported compressive strength of Aramid FRP (AFRP), CFRP and GFRP bars as 10%, 30-50% and 30-40% of tensile strength. Deitz et al. [9] tested 15 mm diameter GFRP bars of varying clear length to diameter ratios with both ends embedded in 50 mm diameter and 135 mm length threaded steel rods by modifying ASTM D695-10 [10] test method for compression testing of rigid plastics. The study recommended clear length to diameter ratios smaller than 7.3, 14 and 25.3 for crushing, combined crushing and buckling, and buckling failures, respectively.

In this experimental study, CFRP and GFRP bars are tested in tension and compression by modifying the ASTM D7205M/7205-06 [3] and ASTM D695-10 [10], respectively. The load-extension and stress-strain of tested FRP bars in tension and compression have been reported.

2 EXPERIMENTAL PLAN

This experimental study reports the tensile testing of three GFRP and three CFRP bars (ASTM D7205M/7205-06 [3]) and compression testing of five CFRP and five GFRP bars (ASTM D695-10 [10]) conducted at High Bay Laboratories, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia.

Tested bars have 100% of the fibres oriented along the longitudinal direction (Pultruded bars). GFRP bars were sand coated whereas CFRP bars were smooth without any coating. Table 1 provides details of diameter and length of GFRP and CFRP bars. Internal and external diameter and length of steel tube anchors used in tensile testing are also reported. Table 2 provides details of diameter and length of GFRP and CFRP bars used in compression testing.

Table 1 Details of Tension test specimens

Type of FRP Reinforcement	Number of Specimens tested	Diameter of FRP bar, D [mm]	Length of FRP bar, L [mm]	Outer Diameter of anchor, D [mm]	Inner Diameter of anchor, D [mm]	Length of anchor, L [mm]
GFRP	3	15.9	1555	45	30	460.0
CFRP	3	15.0	1555	45	30	477.5

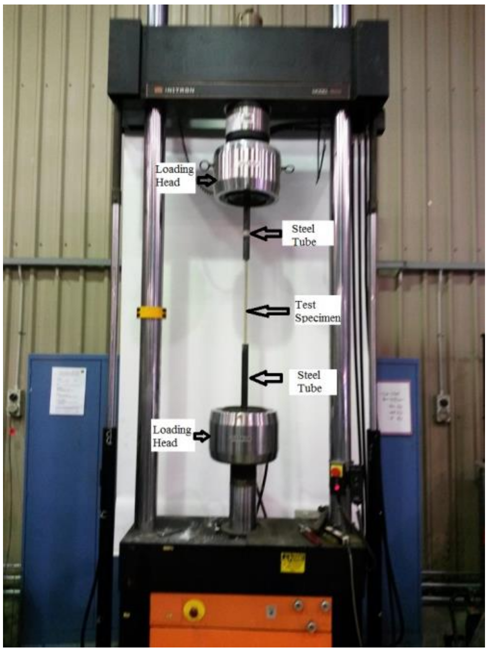
Table 2 Details of Compression test specimens

Type of FRP Reinforcement	Number of Specimens tested	Diameter of FRP bar, D (mm)	Length of FRP bar, L (mm)
GFRP	5	15.9	80
CFRP	5	15.0	60

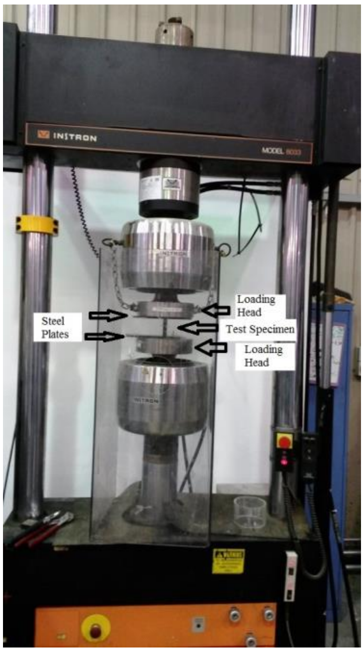
Tested bars were designated according to the type of FRP bars and type of test arrangement and FRP bar number tested in one particular series. This study investigates material properties of two types of FRP bars i.e., GFRP bars (GB) and CFRP bars (CB), under two types of testing arrangements i.e., Tension test (T) and Compression test (C). A number is included to indicate the bar tested in the sequence. For example, CB-T-1 refers to CFRP bar tested in tension and is the first bar.

3 TEST METHODOLOGY

The tension testing of FRP bars was conducted in 500 kN Instron Universal Testing Machine (UTM) while compression testing of FRP bars was conducted in 100 kN Instron UTM (Figure 1). The tension test arrangement consisted of FRP bar embedded in steel tube anchors at the ends. This is because the shear strength of FRP bars is significantly smaller than steel bars and without steel tube anchors FRP bars would fail prematurely at the point of contact with steel grips in the loading heads. The dimensions of steel tube anchors reported here were selected after numerous trials as ASTM D7205M/7205-06 [3] only states the minimum thickness, length and outside and inside diameters of steel tube anchors. Moreover, ASTM D7205M/7205-06 [3] does not cover the tensile testing of 15 mm diameter CFRP bar. To the knowledge of the Authors there is no available study in which 15 mm diameter CFRP bar has been tested in tension. Tested CFRP bars were coated with two layers of coarse sand to increase the friction between bars and steel tube anchors whereas tested GFRP bars were obtained in sand coated condition from the manufacturer. The steel tube anchors of 7.5 mm thickness were filled with expansive cement grout on alternate days as cement grout requires minimum of 16 hours to develop expansive stresses (30 MPa) before grouted steel tube anchor ends could be turned upside down. According to the specifications provided by the manufacturer, expansive cement grout would generate the maximum expansive pressure after 72 hours of casting. FRP bars were tested in tension after 72 hours of casting under the displacement controlled load rate of 1.0 to 1.3 mm per minute to produce rupture of the fibres within the free length (gauge length) of the tested bars (Figure 1 (a)).



(a) Tension testing



(b) Compression testing

Figure 1 Testing arrangement for CFRP and GFRP bars (a) Tension testing (b) Compression testing

To test FRP bars in compression, ASTM D695-10 [10] compression test method for rigid plastics was simplified by replacing the hardened blocks with flat and paralleled high strength steel plates. Moreover, as standard allows for any suitable testing machine which is capable of applying load at a constant controlled load rate hence 100 kN Instron UTM was used for compression testing of FRP bars (Figure 1 (b)). The testing arrangement for compression test consisted of two flat steel plates fixed to the loading heads of the 100 kN Instron UTM. In the laboratory, CFRP and GFRP specimens were cut to the required lengths of 60 mm and 80 mm, respectively. Each compression test specimen with flat parallel ends was placed vertically between the loading heads of the UTM and tested under displacement controlled load at a rate of 1.0 to 1.3 mm per minute until failure.

4 TEST RESULTS AND DISCUSSIONS

This section reports the observed failure, peak load-extension and peak stress-strain of tested FRP bars under tension and compression (Table 3). In tension test, particularly in case of GFRP bars, progressive slippage was observed. It is noted that ASTM D7205M/7205-06 [3] allows a progressive slippage as long as the failure is within the gauge length. It is also noted that the slippage in the case of CFRP bars was smaller compared to the slippage observed in GFRP bars.

Table 3 Experimental results of Tension testing of FRP bars

Specimen ID	Peak Tensile Load [kN]	Ultimate Tensile Extension [mm]	Ultimate Tensile Strength [MPa]	Modulus of Elasticity [GPa]
GB-T-1	258.0	28.3	1307.5	55.6
GB-T-2	278.9	39.4	1409.5	54.8
GB-T-3	290.2	28.0	1467.8	57.5
CB-T-1	199.2	11.7	1127.6	86.9
CB-T-2	211.1	13.1	1195.1	86.7
CB-T-3	202.8	12.0	1148.0	94.6

The observed tensile failure in tested GFRP and CFRP bars was due to tensile rupture of fibres with in the gauge length of bars as shown in Figure 2. This shows that the selected dimensions of steel tube anchors were sufficient to hold FRP bars and prevented uncontrolled slippage.


(a) GFRP bar

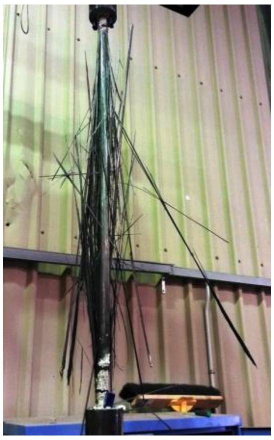
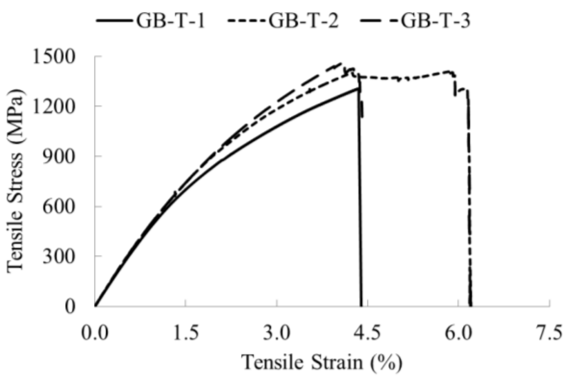
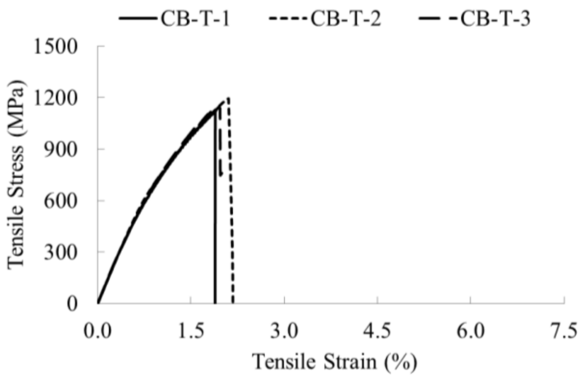

(b) CFRP bar

Figure 2 Observed tensile failure modes in tested FRP bars

The observed tensile stress-strain behaviour of tested FRP bars is presented in Figure 3. The peak tensile stress-strain of GFRP bars was larger than that of CFRP bars. Furthermore, the tensile strength of GFRP bars was about 1.25 times of that of CFRP bars. Modulus of elasticity (*E*) of FRP bars was determined as a gradient of tensile stress-strain curve up to 0.3% tensile strain (ASTM D7205M/7205-06 [3]). Hence the effect of slippage can be ignored in calculating the *E* of tested FRP bars.



(a) GFRP Bars



(b) CFRP bars

Figure 3 Tensile stress-strain in tested FRP bars

The *E* of CFRP bars was 1.6 times of GFRP bars. Although, ASTM D7205M/7205-06 [3] standard allows progressive slippage of bar during the test, due to slippage the ultimate tensile strains obtained from UTM may not be the true ultimate tensile strain of the tested bars. It is recommended to calculate ultimate tensile strain as a ratio of ultimate tensile strength to modulus of elasticity of FRP bar.

The observed peak compressive load-deformation and compressive stress-strain of tested FRP bars is given in Table 4.

Table 4 Experimental results of Compression testing of FRP bars

Specimen ID	Peak Compressive Load [kN]	Peak Compressive Deformation [mm]	Ultimate Compressive Strength [MPa]	Ultimate Compressive Strain [%]	Modulus of Elasticity [GPa]
GB-C-1	183.2	2.1	995.5	2.9	40.0
GB-C-2	147.1	1.9	743.4	2.6	41.5
GB-C-3	155.1	1.8	783.9	2.6	42.0
GB-C-4	159.0	1.9	803.6	2.8	43.3
GB-C-5	178.7	1.9	903.2	2.9	43.3
CB-C-1	100.8	0.9	570.6	1.6	49.7
CB-C-2	109.1	0.8	617.6	1.6	50.0
CB-C-3	103.5	0.9	586.2	1.6	46.4
CB-C-4	105.7	0.8	598.5	2.0	50.0
CB-C-5	107.6	0.9	609.3	1.5	49.2

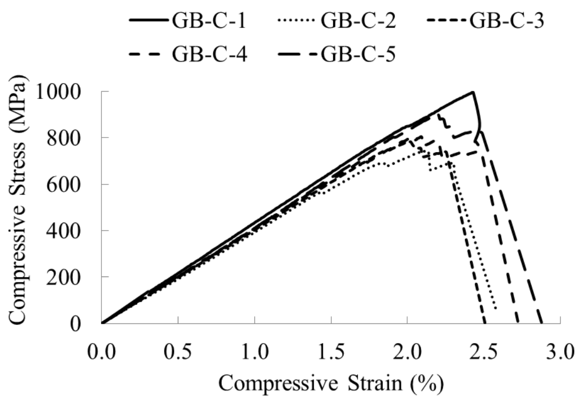
The observed failure modes in the tested GFRP and CFRP bars in compression are shown in Figure 4. It is noted that both types of FRP bars tested in compression failed due to separation of fibres which may be due to failure of the resin rather than buckling of fibres.


(a) GFRP bars

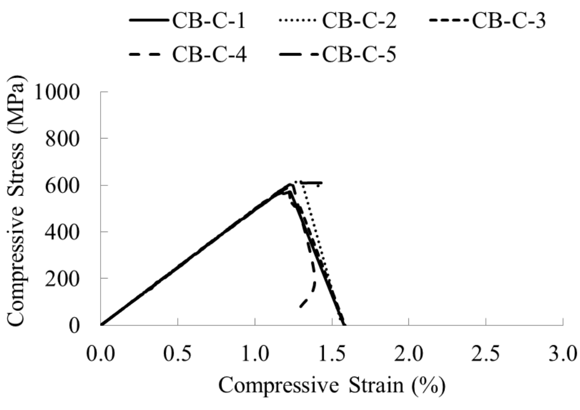

(b) CFRP bars

Figure 4 Observed failure modes in tested FRP bars

The observed compressive stress-strain behaviour of both GFRP and CFRP bars was similar. The observed ultimate compressive stress-strains were higher for GFRP bars than for CFRP bars.



(a) GFRP Bars



(b) CFRP Bars

Figure 5 Compressive stress-strain of tested FRP bars

The variations in compressive stress-strain within the tested GFRP and CFRP bars series were small. The compressive strength values obtained for GFRP bars were 1.4 times higher than CFRP bars, and ultimate compressive strains corresponding to ultimate compressive strength were 1.65 times higher in GFRP bars than in CFRP bars. The ultimate compressive strains of tested FRP bars obtained from tests were reported as recorded in compression test as there is no slippage and values are reliable. The *E* of CFRP bars was 1.17 times greater than GFRP bars. The *E* of GFRP bars (42.0 GPa) obtained in this study is almost identical to the value (42 GPa) reported by Deitz et al. [9]

5 CONCLUSIONS

This experimental study reports the load-extension and stress-strain behaviours of the tested CFRP and GFRP bars under tension and compression. The main conclusions of this experimental study are as follows;

The modified test methods adopted in this study for tension and compression tests of 15.9 mm and 15 mm diameters GFRP and CFRP bars, respectively were successful and could be adopted for testing of other types and diameter of FRP bars.

GFRP bars attained higher load-extension and stress-strain in both tension and compression than CFRP bars for the same nominal diameter.

The ultimate tensile strengths of GFRP and CFRP bars were 65% and 94% higher than their ultimate compressive strengths, respectively.

The tensile modulus of elasticity of GFRP and CFRP bars were 33% and 89% higher than their compressive modulus of elasticity, respectively.

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